



Physical and textural attributes of rice-sweet potato-watermelon seed extruded snacks: influence of extrusion process conditions

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Abstract

The combination of rice flour, sweet potato flour, and watermelon seed powder remains a relatively unexplored resource within the realm of extruded snacks production. Thus, this study investigated the effect of three extrusion process parameters: feed moisture content (FMC, 16-18%), exit barrel temperature (EBT, 120-140 °C), and barrel screw speed (BSS, 300-420 rpm) on rice-sweet potato-watermelon seed extruded snacks. Physical (bulk density, expansion ratio) and textural properties (hardness, fracturability, chewiness, gumminess, and stringiness) were measured using standard procedures. Statistical analysis identified the most influential parameters, with Pareto charts at a 95% confidence level and contour plots visualizing their impacts. Results showed significant variations: bulk density (0.22-0.73 g/cm³), expansion ratio (2.25-2.58), hardness (54.01-464.95 N), fracturability (22.65-176.28 N), chewiness (0.02-5 N), gumminess (0.86-41.84 N), and stringiness (4.83-5.20 mm). EBT had the greatest impact on expansion ratio, while FMC significantly affected hardness, fracturability, chewiness and gumminess, and BSS influenced bulk density and stringiness. The study concluded that extrusion conditions critically shape the physical and textural attributes of the products, providing valuable insights for optimizing extrusion settings to achieve desired textural profiles and enhance overall snack quality.

Keywords: Extruded snacks, Extrusion cooking, Physical properties, Rice flour, Sweet potato, Textural properties, Watermelon seed

1. Introduction

Extruded snacks have become essential to daily food consumption due to their convenience and nutritional value [1]. These snacks are designed to meet specific quality standards and can contribute to nutrition in societies where traditional food preparation patterns are changing [2]. Extrusion cooking is a versatile technology used in snack production that helps to reduce antinutritional factors in food, increase nutritional stability, and create nutrient-rich products with a long shelf life [3]. Extruded snacks can be produced with low fat content and without salt or sugar, making them a preferred choice for children's diets [4]. These snacks can also be enriched with fruits, vegetables, and industrial by-products, providing additional health benefits such as fibre and antioxidants [5].

In addition to their nutritional profile, the physical and textural properties of extruded snacks are essential to their success. The physical properties, such as expansion ratio, bulk density, and porosity, are crucial in determining the overall quality and appeal of the extruded products [2]. Texture is another critical attribute that affects consumer perception and satisfaction. It can be measured through instrumental analysis, which provides parameters such as

hardness, fracturability, chewiness, gumminess, and stringiness. The optimization of extrusion conditions, including the selection of ingredients and processing parameters, can help improve these attributes, resulting in products that are more appealing to consumers.

Sweet potatoes (*Ipomoea batatas*) are major root crops widely utilized for their diverse food applications. They are a versatile ingredient in baked goods, such as bread, cookies, and pancakes. Sweet potato can hold moisture in baked goods, resulting in a moist and tender texture. Additionally, sweet potato flour can add natural sweetness, colour, and flavour to processed food products. It is an excellent alternative to wheat flour and can replace 100% of the flour in cookies and cakes [6]. Sweet potato flour is also rich in nutrients, including fibre, minerals, vitamins, and antioxidants, while having a low fat content [7]. Watermelon seeds are nutrient-dense and contain proteins, vitamins, omega-3 and omega-6 fatty acids, magnesium, zinc, copper, and potassium [1, 8]. These seeds are high in calories; thus, it is essential to consume them in regulated portions. Watermelon seeds provide significant benefits to the body, such as improving heart health, lowering blood sugar levels, and boosting overall immunity [9]. Broken rice refers to fragments of rice grains that are as nutritious as the equivalent quantity of unbroken rice. It provides energy, carbohydrates, calcium, iron, thiamine, pantothenic acid, folate, and vitamin E [10]. Incorporating broken rice flour into extruded snacks can improve their nutritional value and sustainability. Notable studies include: the physical properties of pigmented rice snacks [2]; physicochemical properties of sweet potato snacks [11]; textural, sensory, and functional properties of pulses and pseudocereal proteins [12]; and the functionality of corn and carrot powder [13]. Furthermore, Nagaraju et al. [14] investigated the effect of extrusion on the physical and functional properties of millet-based extrudates. Although significant research has been conducted in this area, there is limited literature on the physical and textural properties of extruded blends incorporating broken rice, sweet potato, and watermelon seed. Therefore, exploring the impact of extrusion conditions on the physical and textural properties of rice–sweet potato–watermelon seed snacks can aid in developing competitive and consumer-friendly products. This study aimed to evaluate these effects.

2. Materials and Methods

2.1 Study Area and Material Procurement

The study was conducted in the Department of Food Engineering, University of Ilorin, Nigeria. Broken rice and watermelon seeds were sourced from 3Q Rice Mill and FDE Juice Processing Company in Ilorin, respectively. Sweet potato flour was obtained from Benedict General Agro Supplies in Ibadan, Oyo State, Nigeria.

2.2 Material Preparation

A total of 5 kg of watermelon seeds was thoroughly washed to remove impurities and residues. After washing, the seeds were dried in a forced-air dryer at 60 °C for 30 minutes to ensure uniform moisture removal. The dried seeds were then ground into flour using a grinder (Model: FP-850, China) to produce a consistent powder suitable for further processing. Similarly, 17 kg of broken rice was processed to obtain rice flour. The rice was milled using a hammer mill (Model: Nukor, SG 30, South Africa) to ensure a uniform particle size. After milling, the rice flour was stored in sealed polyethylene bags to prevent moisture absorption and contamination. The packaged flour was then kept at room temperature in a cool, dry environment to preserve its quality for subsequent snack formulation.

2.3 Experimental Design

The study utilized a Taguchi Orthogonal Array within a Response Surface Methodology (RSM) framework to assess the impact of three extrusion parameters: barrel screw speed (300, 360, and 420 rpm), exit barrel temperature (120, 130, and 140 °C), and feed moisture content (16, 17, and 18%). The study evaluated the effects of these parameters on the physical and textural properties of rice–sweet potato–watermelon seed extruded snacks. Taguchi design results were analyzed using the RSM second-order polynomial model to evaluate linear, quadratic, and interaction effects on expansion ratio, bulk density, hardness, fracturability, chewiness, gumminess, and stringiness. Analysis of variance (ANOVA) was used to determine statistical significance at a 95% confidence level, with Fisher's values (F-values) utilized for model quality assessment. Significant parameters were identified using Pareto charts in Minitab 20.3, with a reference line indicating statistical significance at $\alpha = 0.05$.

2.4 Extrusion Process of Rice-Sweet Potato-Watermelon Seed Extruded Snacks

Figure 1 illustrates the extrusion process for the rice–sweet potato–watermelon seed snacks. A co-rotating twin-screw extruder (Model: HN-65, China) was utilized for the process. The formulation comprised a mixture of rice flour, sweet potato flour, and watermelon seed powder blended in a ratio of 53:41:6, respectively. This specific ratio was chosen for its protein content of 20.07%, which enhances the nutritional value of the final product. To ensure proper hydration, potable water was incorporated into the flour blend at three levels (16%, 17%, and 18% w/w) using a mixer (Model: Cx-6612, China). The extruder barrel consisted of three heating zones; the first and second zones were maintained at 80 °C and 100 °C, respectively, while the exit barrel temperature (EBT) was adjusted between 120 °C and 140 °C according to the experimental design. The prepared blends were fed into the extruder hopper at a constant feed rate of 120 rpm. Inside the barrel, the material was processed at varying screw speeds (300–420 rpm), where intense mechanical shear and thermal processing transform the blend into a homogeneous extrudate. Upon reaching the die section, the extrudate was forced through a 4 mm diameter circular die and cut into uniform pieces using a rotating blade cutter operating at 1500 rpm. The extrudates were cooled and dried in a forced-air dryer at 42 °C for 25 minutes to reduce moisture content and enhance shelf stability. Finally, the dried products were packed into Ziploc bags and stored at room temperature to prevent moisture uptake and microbial contamination.

2.5 Evaluation of Physical Properties

The bulk density of each extrudate was measured using methods described by Meng *et al.* [15] through a volumetric displacement procedure. The expansion ratio was calculated as the ratio of the extrudate cross-sectional diameter to the die diameter [15].



Figure 1 Schematic of the extrusion process for rice–sweet potato–watermelon seed blends using a co-rotating twin-screw extruder

2.6 Evaluation of Textural Attributes

Textural attributes were analyzed using a Texture Analyzer (Stable Micro Systems, Godalming, UK) following a modified method by Wójtowicz *et al.* [5]. A 36 mm diameter aluminum cylindrical probe with a 30 kg load cell performed a Texture Profile Analysis (TPA) double compression test. The test was conducted at a pre-test and test speed of 200 mm/min to 50% of the sample height, assessing hardness, fracturability, chewiness, gumminess, and stringiness, with a 5 s recovery period between strokes.

2.7 Statistical analysis

Triplicate samples of the rice–sweet potato–watermelon seed extruded snacks were analyzed, with results expressed as means $\pm$ standard deviation. Descriptive statistics and one-way ANOVA were performed using IBM

SPSS Statistics 20.0 (SPSS Inc., Chicago, IL, USA), with Duncan's Multiple Range Test (DMRT) used to determine significant differences among the means at $p < 0.05$. Additionally, the Taguchi Orthogonal Array and Response Surface Methodology (RSM) were analyzed using Minitab 20.3 (Minitab Inc., State College, PA, USA) to identify influential parameters and generate Pareto charts and contour plots for process optimization.

3. Results and Discussion

3.1 Physical Properties

Table 1 presents the effects of EBT, BSS, and FMC on the bulk density and expansion ratio of rice–sweet potato–watermelon seed extruded snacks. Bulk density ranged from 0.26 to 0.73 g/cm³, with significant differences observed ($p < 0.05$) among the samples. The linear effect of barrel screw speed (BSS) was found to be the most significant factor influencing bulk density, as shown in the Pareto chart (Figure 2A). This is likely due to the high mechanical shear associated with increased speeds. This finding aligns with the observation of Pardhi et al. [16] that BSS largely influences the bulk density of extrudates produced from brown rice grits. Figure 2B illustrates that lower EBT and BSS resulted in higher bulk density (darker green regions). This may be attributed to reduced starch gelatinization and lower melt fluidity at these conditions, leading to an inverse relationship between these parameters and bulk density. Nagaraju et al. [14] observed a similar phenomenon in millet-based extrudates. In this study, Figure 2C indicates that an increase in FMC led to a decrease in bulk density. This result is supported by the studies of Nishani et al. [17] and Ding et al. [18], who found that higher moisture levels can lower bulk density in certain cereal-based snacks by acting as a plasticizer that enhances melt fluidity. This observation, however, contrasts with the trends reported by Filli et al. [19] and Yatin et al. [20], where increased FMC hindered expansion and raised bulk density in millet–soybean formulations. The discrepancy suggests that the impact of moisture on bulk density is highly dependent on the specific starch-protein-fibre matrix. In the current blend, the high starch content from rice and sweet potato likely maintained sufficient elasticity for expansion even at higher moisture levels, whereas the water retention effect noted by Nishani et al. [17] may only occur at much higher moisture thresholds than those tested here.

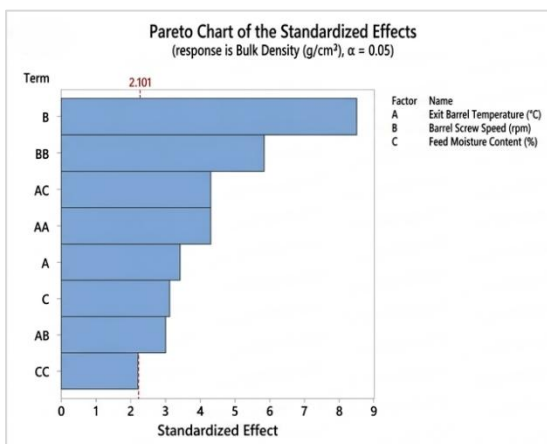
Table 1 Bulk density and expansion ratio of rice-sweet potato-watermelon seed extruded snacks

Sample	FMC (%)	EBT (°C)	BSS (rpm)	BD (g/cm ³)	ER
X1	16	140	300	0.43±0.07 ^c	2.39±0.29 ^{ab}
X2	17	140	360	0.33±0.03 ^d	2.58±0.14 ^a
X3	18	140	420	0.39±0.04 ^c	2.47±0.22 ^{ab}
X4	17	120	300	0.73±0.07 ^a	2.31±0.20 ^b
X5	18	120	360	0.22±0.02 ^d	2.25±0.34 ^b
X6	16	120	420	0.43±0.05 ^c	2.46±0.20 ^{ab}
X7	18	130	300	0.45±0.08 ^b	2.37±0.26 ^{ab}
X8	16	130	360	0.29±0.03 ^d	2.38±0.19 ^{ab}
X9	17	130	420	0.29±0.02 ^d	2.39±0.22 ^{ab}

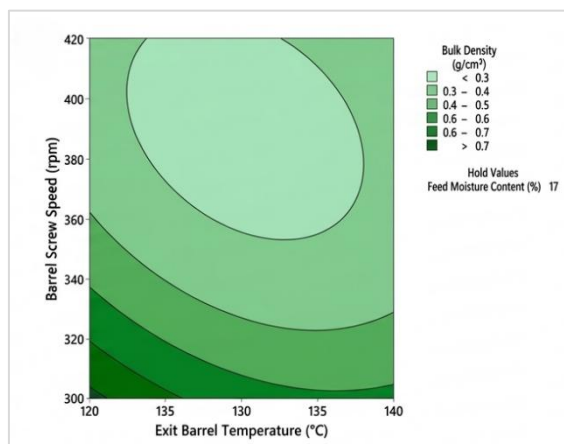
Mean values in the same column with different superscript letters indicate significant differences at $p < 0.05$. FMC – Feed Moisture Content; EBT–Exist Barrel Temperature; BSS – Barrel Screw Speed; BD – Bulk Density; ER – Expansion Ratio

The expansion ratio indicates the degree of puffing of extruded products. The mean expansion ratio under the tested extrusion conditions ranged from 2.25 to 2.58 (Table 1). The highest expansion ratio (2.58) was observed at 17% FMC, 360 rpm BSS, and 140°C EBT. Figure 3A indicates that the linear effect of EBT significantly affects the expansion ratio. This is consistent with Azam and Singh [21] and Naveenah and Singh [22] and Sanusi et al. [23], who reported a significant effect of barrel temperature on the expansion ratio of kodo-based, fermented chickpea-based extrudates and wheat-rice-sweet potato of 3G snacks, respectively. As shown in Figures 3B and 3C, an increase in EBT and FMC promoted a higher expansion ratio, while a decrease in BSS also contributed to an increased ratio. The higher expansion at elevated temperatures can be attributed to enhanced starch gelatinization and increased vapour pressure during processing. Moisture in the feed blends acts as a plasticizer and binder, facilitating the phase transition of starch and fibre during extrusion. Furthermore, it promotes the melt elasticity of the blend, which directly influences the degree of expansion at the die.

(A)



(B)



(C)

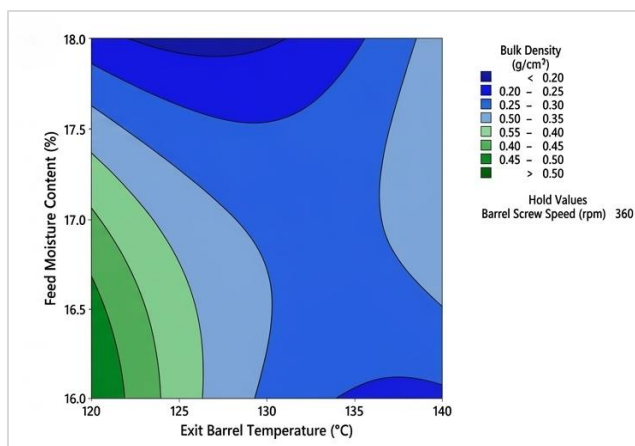
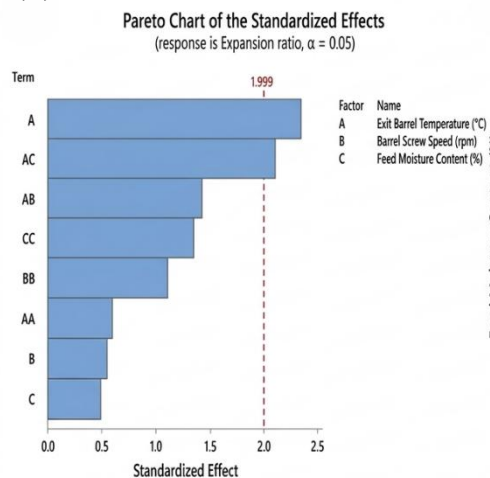
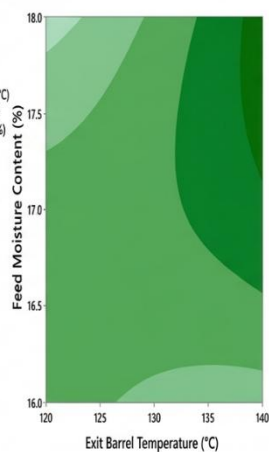


Figure 2 (A) Pareto chart of extrusion conditions on bulk density; (B) Contour plot of FMC and EBT on bulk density; (C) Contour plot of BSS and EBT on bulk density

(A)



(B)



(C)

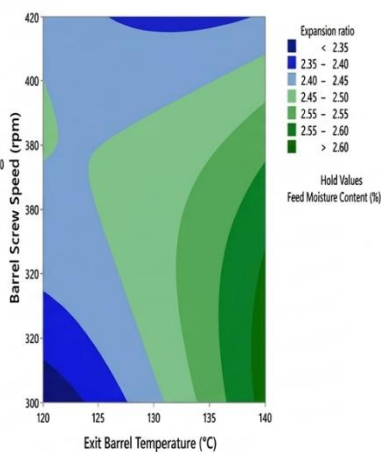


Figure 3 (A) Pareto chart of extrusion conditions on expansion ratio; (B) Contour plot of FMC and EBT on expansion ratio; (C) Contour plot of BSS and EBT on expansion ratio

3.2 Textural Properties

Textural properties are essential quality attributes that dictate the consumer acceptability of extruded products. As shown in Table 2, the textural profile of the rice–sweet potato–watermelon seed snacks varied significantly; hardness ranged from 54.01 to 464.95 N, while fracturability ranged from 22.65 to 176.28 N. In this study, hardness represents the peak force required for deformation, whereas fracturability indicates the force at which the internal structure of the extrudate shatters. Generally, a positive correlation was observed between the two, as harder snacks exhibited higher brittleness. The Pareto charts (Figures 4a and 4b) confirm that Feed Moisture Content (FMC) was the most significant factor influencing both textural properties, with the standardized effect clearly crossing the statistical significance threshold ($p < 0.05$). Both hardness and fracturability reached their maximum values at the highest tested FMC of 18%. This trend is clearly illustrated in the corresponding contour plots (Figures 5A and 5C), where the dark green regions, representing peak textural resistance, are concentrated at high moisture levels. High FMC typically increases hardness by increasing melt density and suppressing volumetric expansion. These findings corroborate the results of Ding et al. [18] and Liu et al. [11] regarding the texture of expanded starch-based snacks.

Conversely, the lowest values for hardness and fracturability were observed at the highest Exit Barrel Temperature (EBT) of 140°C. This suggests that the reduction in melt viscosity at elevated temperatures favoured rapid bubble growth and enhanced expansion, resulting in a low-density, softer extrudate. Similarly, high Barrel Screw Speed (BSS) contributed to a softer texture (Table 2), likely due to intense mechanical shear reducing the molecular weight of the starch polymers, an observation consistent with Chakraborty et al. [24]. While the Pareto charts identify the dominance of the moisture effect, the contour plots in Figure 5 further reveal that the softening effect of high EBT is most pronounced when the moisture content is kept at lower levels, demonstrating a clear interaction between thermal and moisture parameters.

Table 2 Textural attributes of rice-sweet potato-watermelon seed extruded snacks

Sample	EBT (°C)	BSS (rpm)	FMC (%)	H (N)	Fr (N)	G (N)	S (mm)	Cw (N)
X1	140	300	16	69.81 ^d	28.38 ^{de}	0.86 ^c	5.11 ^{ab}	0.02 ^b
X2	140	360	17	54.01 ^d	22.65 ^e	1.73 ^c	5.20 ^a	0.03 ^b
X3	140	420	18	109.65 ^{cd}	87.85 ^c	3.00 ^{bc}	5.07 ^{ab}	0.08 ^b
X4	120	300	17	162.44 ^c	52.79 ^{de}	6.65 ^{bc}	5.10 ^{ab}	0.13 ^b
X5	120	360	18	282.81 ^b	137.33 ^b	10.34 ^b	5.03 ^b	0.40 ^b
X6	120	420	16	139.95 ^{cd}	87.49 ^c	4.79 ^{bc}	5.15 ^{ab}	0.09 ^b
X7	130	300	18	464.95 ^a	176.28 ^a	41.84 ^a	4.83 ^c	5.00 ^a
X8	130	360	16	113.67 ^{cd}	29.27 ^{de}	1.27 ^c	5.09 ^{ab}	0.02 ^b
X9	130	420	17	89.49 ^{cd}	59.82 ^{cd}	2.06 ^c	5.20 ^a	0.04 ^b

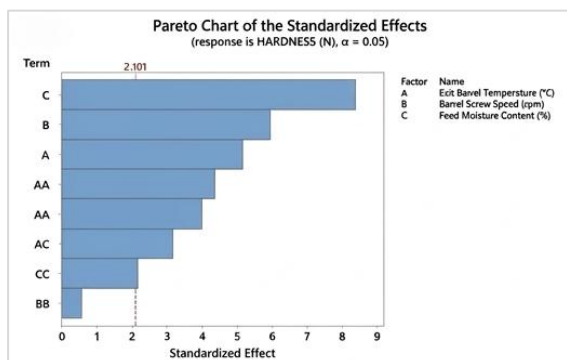
Mean values in the same column with different superscript letters indicate significant differences at $p < 0.05$. FMC – Feed Moisture Content; EBT–Exit Barrel Temperature; BSS – Barrel Screw Speed; H–Hardness; Fr – Fracturability; Cw – Chewiness; G – Gumminess; S – Stringiness

Figures 5A–D illustrate the influence of processing variables on the hardness and fracturability of the extruded snacks. Contrary to some previous findings, the results show that while higher Feed Moisture Content (FMC) increases these values, a higher Exit Barrel Temperature (EBT) actually tends to decrease them. At lower FMC and higher EBT, the extrudates exhibited lower hardness and fracturability. The increment in fracturability with FMC may be attributed to reduced expansion, increased product density, and slower starch gelatinization. Similar results were reported by Sahu and Patil [25] in the development of maize-millet-fortified extruded products. Chewiness represents the effort required to break down a food product during mastication, reflecting how tough or resistant a snack feels. Gumminess, on the other hand, reflects the energy required to disintegrate food into a state ready for swallowing. The chewiness and gumminess values of the extruded snacks ranged from 0.02 to 5.00 N and 0.86 to 41.84 N, respectively (Table 2). As shown in Figures 5E–H, these attributes increased with higher FMC but decreased with higher Barrel Screw Speed (BSS). This aligns with Wójtowicz et al. [5], who noted that higher FMC increases chewiness. However, it contradicts the findings of Wójtowicz et al. [26], who reported that the chewiness of extruded gluten-free snacks supplemented with fruit increases with BSS.

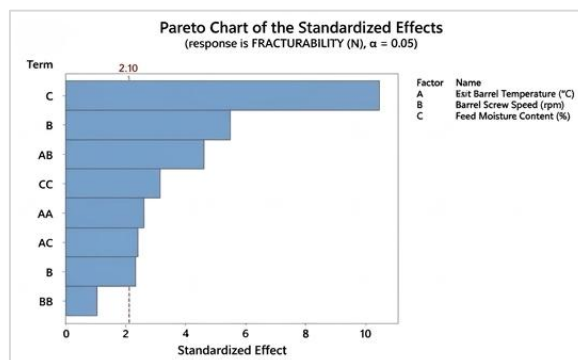
The gumminess of the rice–sweet potato–watermelon seed extrudates was primarily governed by Feed Moisture Content ($p < 0.05$), as illustrated in the Pareto Chart (Figure 4D). The positive correlation between FMC and gumminess (Figure 5H) suggests that water acts as a plasticizer that enhances the cohesiveness of the starch-fiber melt, resulting in a more integrated internal structure. Conversely, the reduction in gumminess at higher Barrel Screw Speeds may be attributed to the mechanical shearing of starch granules, which reduces the melt viscosity and

subsequent structural resilience. This finding is consistent with Sanusi et al. [27], who reported that gumminess in brown rice-watermelon extruded snacks increases with higher FMC and EBT. Stringiness is associated with the stickiness and elongation of snacks when chewed; lower stringiness typically indicates a more favourable, brittle texture. The stringiness of the extruded snacks ranged from 4.83 to 5.20 mm. The Pareto chart (Figure 4E) shows that BSS is the primary influence on stringiness. This could be attributed to the principle of elasticity, where the elasticity modulus increases with applied force. Similar findings were reported by Liu et al. [28] for extruded corn puffs. As shown in Figures 5I and 5J, increases in BSS and EBT led to higher stringiness, while lower FMC combined with higher EBT or BSS further enhanced this property.

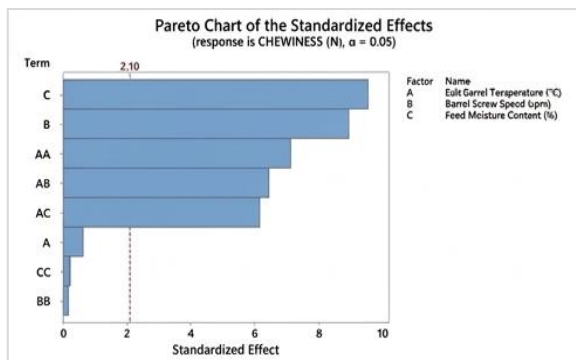
(A)



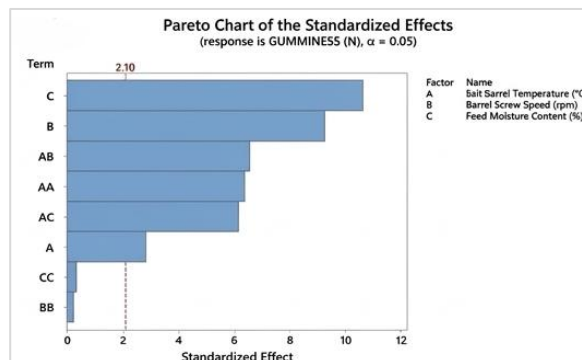
(B)



(C)



(D)



(E)

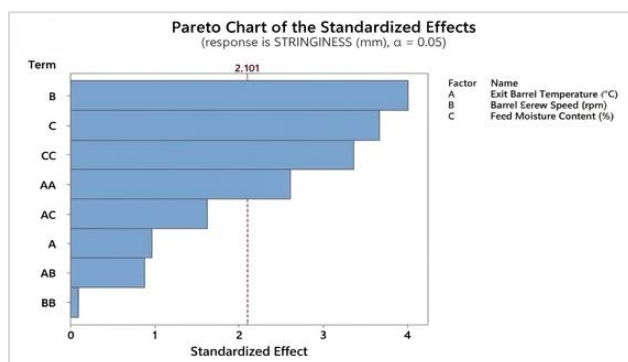


Figure 4 Pareto chart of textural attributes of rice-sweet potato-watermelon seed extruded snacks

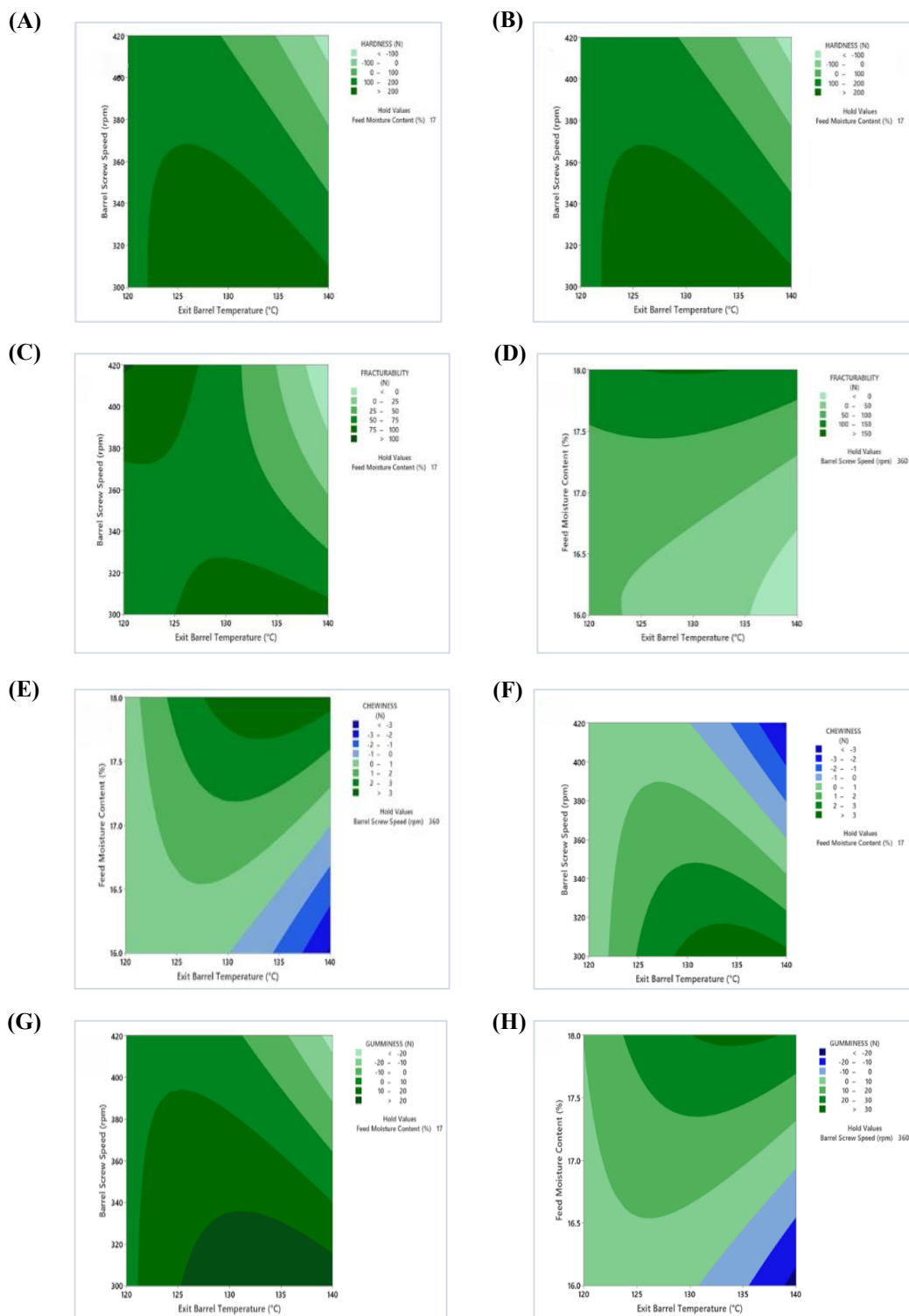


Figure 5 Contour plots depicting the textural attributes (Hardness (A&B), Fracturability (C&D), Chewiness (E&F), Gumminess (G&H), and Stringiness (I&J) of rice-sweet potato-watermelon seed extruded snacks.

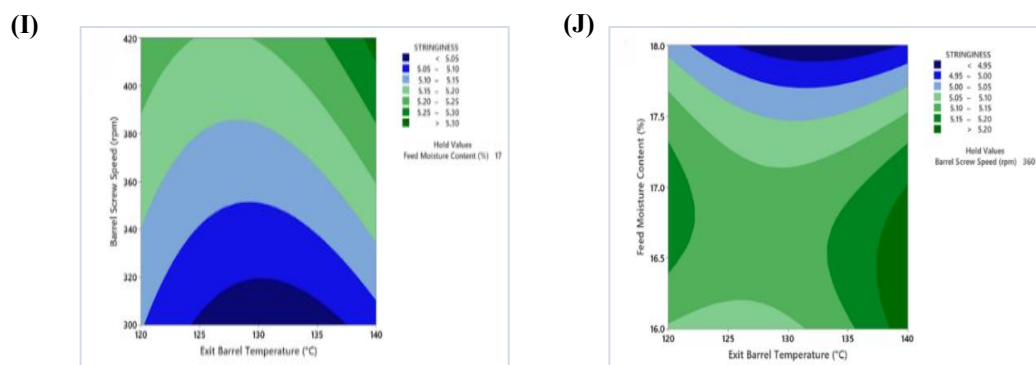


Figure 5 Contour plots depicting the textural attributes (Hardness (A&B), Fracturability (C&D), Chewiness (E&F), Gumminess (G&H), and Stringiness (I&J) of rice-sweet potato-watermelon seed extruded snacks. (Cont.)

4. Conclusions

In this study, extruded snacks were successfully developed from a composite blend of rice flour (53%), sweet potato flour (41%), and watermelon seed powder (6%). The physical and textural properties were evaluated, revealing that extrusion parameters significantly dictated final product quality. Feed Moisture Content (FMC) emerged as the dominant factor influencing textural attributes, specifically hardness, fracturability, gumminess and chewiness. Barrel Screw Speed (BSS) primarily affected bulk density and stringiness, while Exit Barrel Temperature (EBT) exerted the greatest impact on the expansion ratio. This study demonstrates that precise control of extrusion variables is essential for tailoring the physical and textural characteristics of rice–sweet potato–watermelon seed snacks. Furthermore, it provides a technical framework for optimizing production processes to deliver high-quality, functional extruded products.

5. Acknowledgements

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6. Conflicts of interest

The authors declare that they have no conflict of interest.

7. Author Contributions

Mayowa S. Sanusi: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Project administration, Writing - Review & Editing and Supervision; Abdulkareem B. Bello: Methodology, Investigation, Validation, Data Curation, Supervision, Writing - Review & Editing; Hamidu O. Sanusi: Software, Formal analysis, Visualization, Supervision, Writing - Review & Editing; Toheeb B. Olaniran: Supervision, Conceptualization, Writing - Review & Editing; Eniola D. Adebayo: Investigation, Data Curation, Resources; Ghali M. Yakub: Investigation, Data Curation, Resources; Hafsat F. Bankole: Investigation, Data Curation, Resources; Oreoluwa T. Abodunrin: Investigation, Visualization, Data Curation, Resources; Israel A. Adeniyi: Investigation, Resources, Validation, Data Curation.

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